Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **24**, 1213–1228 (1999)

PARAGLACIAL MODIFICATION OF SLOPE FORM

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Received 3 November 1998; Revised 8 May 1999; Accepted 21 May 1999

ABSTRACT

The morphological consequences of paraglacial modification of valley-side drift slopes are investigated at six sites in Norway. Here, paraglacial slope adjustment operates primarily through the development of gully systems, whereby glacigenic sediment is stripped from the upper drift slope and redeposited in debris cones downslope. This results in an overall lowering of average gradient by up to 4·5° along gully axes. In general, slope profile adjustment appears to be characterized by a convergence of slope profiles towards an 'equilibrium form' with an upper rectilinear slope gradient at 29° ± 4° and a range of concavities of approximately 0·0 to 0·4. After initial rapid incision, further gully deepening is limited, but gullies become progressively wider as sidewall gradients decline to *c*. 25°, after which parallel retreat appears to predominate. The final form of mature paraglacial gully systems consists of an upper bedrock-floored source area, a mid-slope area of broad gullies whose sidewalls rest at stable, moderate gradients, and a lower slope zone where gullies discharge onto the surfaces of debris cones and fans. Some gullies appear to have attained this final form and have stabilized following exhaustion of readily entrainable sediment within decades of gully initiation. At most sites, paraglacial activity has transformed steep drift-mantled valley sides into gullied slopes where an average of *c*. 2–3 m of surface lowering has taken place. At the most active sites, these average amounts imply minimum erosion rates averaging *c*. 90 mm a^{-1} since gully initiation, which highlights the extreme rapidity of paraglacial erosion of deglaciated drift-mantled slopes.

KEY WORDS: paraglacial; glacigenic drift; gully; slope profile; debris flow; Norway

INTRODUCTION

The term 'paraglacial' was defined by Church and Ryder (1972, p. 3059) as referring to 'nonglacial processes that are directly conditioned by glaciation', and was initially employed to describe the reworking of glacigenic sediments by fluvial processes and debris flows following glacier retreat. However, most studies of paraglacial resedimentation of valley-side glacigenic drift have paid little attention to the effects of paraglacial activity in modifying slope form. Research which specifically considers paraglacial modification of the form and behaviour of steep drift slopes is largely confined to work carried out in two recently deglaciated Norwegian valleys by Ballantyne and Benn (1994, 1996) and Ballantyne (1995). These authors found that paraglacial drift modification in Fåbergstølsdalen since AD 1943 had led to localized reduction of overall slope gradients by *c*. 5°, and that slope-foot debris cone accumulation had contributed to a general reduction in overall slope concavity. They also calculated minimum average rates of slope surface lowering due to gullying at particular sites of 50–100 mm a^{-1}, and estimated a maximum rate of 200 mm a^{-1} at one location. The wider representativeness of their findings is unknown, however, and, in particular, their predictions as to how paraglacial gully systems evolve remain untested. The research reported in this paper addresses these issues by (1) describing how drift slope long profiles are modified by gullying, (2) explaining how gullies develop through time and (3) assessing the rates of slope adjustment involved, in a wide range of field situations in Norway.

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Contract/grant sponsor: University of St Andrews
Contract/grant sponsor: Russell Trust
Contract/grant sponsor: Quaternary Research Association

CCC 0197-9337/99/131213–16 $17.50

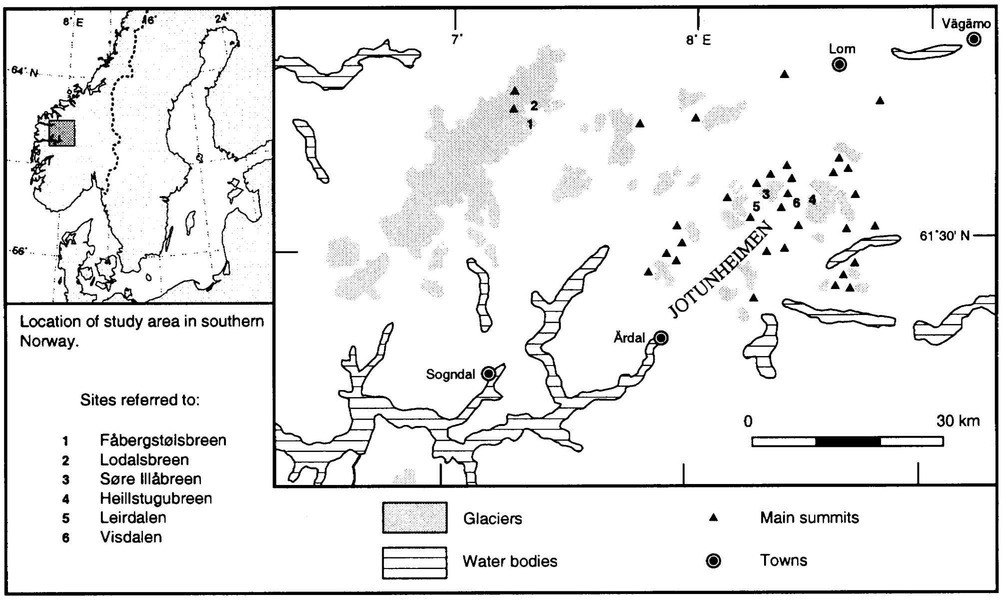


Figure 1. Location of the field sites

Figure 2. The glacier foreland of Fåbergstølsbreen, showing the extensive paraglacial gully systems incised into thick valley-side drift

Table I. Dimensions of gully systems surveyed at sites in Norway

Profile	Maximum depth (m)	Length (m)	Mean width (m)	Volume (10^3 m^3)
Fåbergstølsbreen				
Fa	4·0	53	5·3	0·59
Fb	9·1	95	5·8	1·27
Fc	9·2	98	5·0	2·25
Fd	11·1	78	34·1	7·98
Fe	7·4	51	23·0	3·89
Lodalsbreen				
La	5·0	96	12·1	1·23
Lb	6·8	97	8·2	2·58
Lc	16·0	75	15·1	8·71
Ld	7·2	192	31·6	5·21
Søre Illåbreen				
Sa	1·2	12·4	2·1	0·016
Sb	1·5	14·1	1·9	0·020
Heillstugubreen				
Ha	1·6	6·4	4·4	0·015
Hb	1·6	29·9	8·9	0·165
Hc	1·3	19·7	4·9	0·063
Hd	1·0	34·2	8·3	0·126
Leirdalen				
LEa	4·0	369	17·2	7·67
LEb	6·8	202	44·8	23·79
LEc	5·2	205	32·8	11·22
LEd	12·8	247	63·5	69·58
LEe	10·0	277	63·0	49·76
Visdalen				
Va	14·8	210	45·0	67·78
Vb	14·0	310	61·5	65·67
Vc	7·2	241	37·4	22·79
Vd	8·0	235	48·2	38·86
Ve	7·2	112	31·0	8·26

STUDY AREA AND METHODS

The morphological consequences of paraglacial modification of valley-side drift slopes were investigated on the forelands of two outlet glaciers (Fåbergstølsbreen and Lodalsbreen) which drain the Jostedalsbre ice cap in southern Norway (61°40′ N, 7°05′ E), on the Søre Illåbre and Heillstugubre glacier forelands in Jotunheimen (61°30 N, 8°20′ E), and within Leirdalen and Visdalen, also in Jotunheimen (Figure 1). All the sites were deglaciated by *c*. 9 ka BP (Shakesby *et al*., 1990; Nesje *et al*., 1991), but the four forelands were reoccupied by glacier ice during the Little Ice Age (Matthews and Shakesby, 1984; Bickerton and Matthews, 1993). These glaciers then underwent net retreat, which exposed steep slopes mantled by glacigenic deposits. Such deposits have subsequently been locally reworked by paraglacial debris-flow activity, with the formation of deep gullies on some upper slopes and of cones of reworked sediment at the slope foot (Ballantyne and Benn, 1994; Curry and Ballantyne, 1999; Figure 2).

Assessment of paraglacial modification of slope form at these sites involved both instrumental survey of slope profiles and measurement of the dimensions of gullies incised into hillslope drift. At each field site, slope profiles were surveyed where fragments of unmodified drift (i.e. the slope at the time of deglaciation) survive beside gullies. To assess the influence of gully development on slope form, parallel profiles were

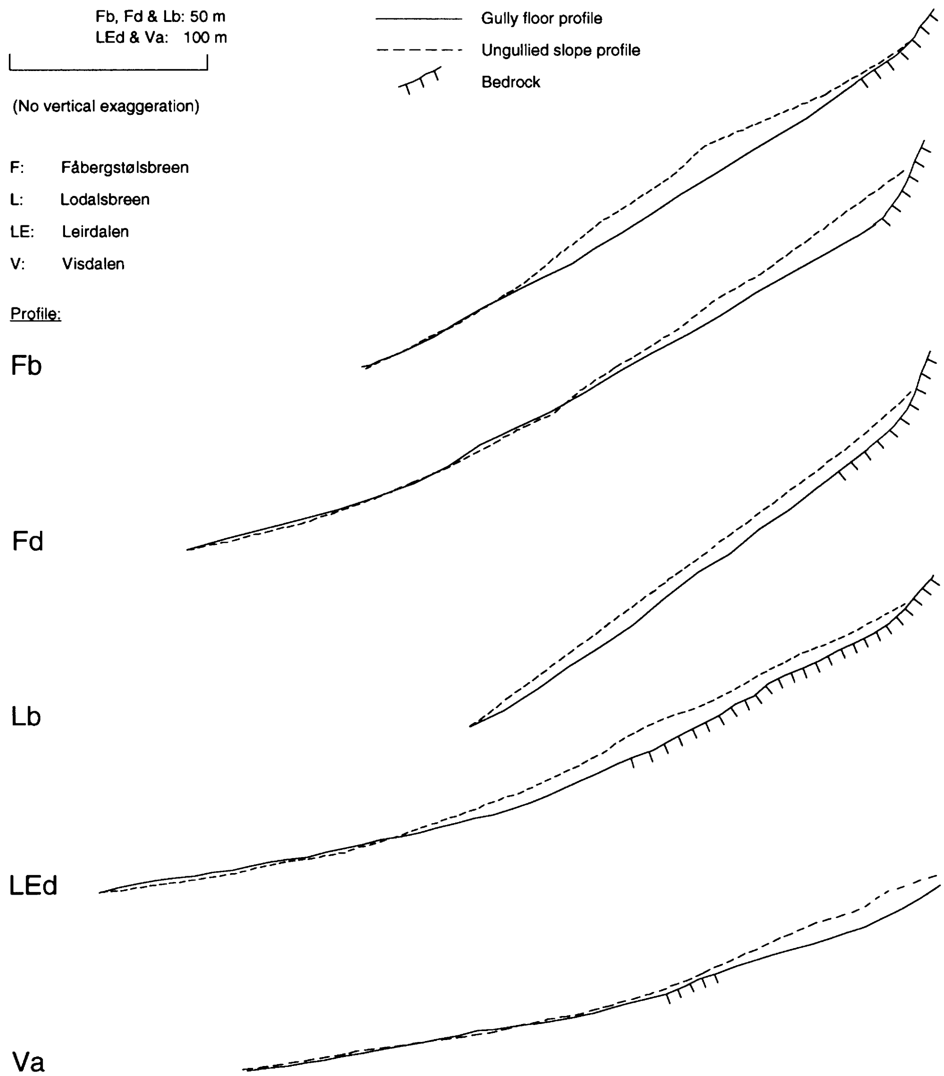


Figure 3. Five slope profiles illustrating the modification in profile characteristics due to gullying of valley-side drift at sites in Norway

surveyed up paired gully floors and adjacent unmodified slopes. Transects were also surveyed across the gullies to allow calculation of gully volume and hence implied sediment loss, and to allow trends in gully form to be identified. The dimensions of the surveyed gullies are summarized in Table I. To allow comparative quantitative analysis of the paired slope profiles, three measures were used to describe slope gradient and geometry. The overall mean slope angle (α) measures the average gradient of the entire drift slope profile from foot to crest. The form of the upper straight slope is summarized by the upper rectilinear slope angle (α_u), defined as the average slope angle excluding any upper slope convexity and the basal concavity. Finally, the index of concavity (c) employed here was proposed by Church *et al.* (1979) to describe overall debris slope morphology. This index is calculated in terms of the ratio of convex and concave elements of the slope (Church *et al.*, 1979), and describes slopes as 'concave' (where $c \leq 0{\cdot}125$), 'concave, minor convexity' (where $0{\cdot}125 < c \leq 0{\cdot}75$), 'convex–concave' (where $0{\cdot}75 < c \leq 1{\cdot}25$) or 'convex, minor concavity' (where $1{\cdot}25 < c \leq 8{\cdot}75$).

Table II. Slope gradient and geometry of ungullied drift slopes (UD) that represent the gradient and geometry of deglaciated drift slopes prior to modification by debris flow, gully floors (GF) that represent the gradient and geometry of paraglacially modified valley-side slopes, and the difference between each (Δ) at the field sites

Profile	Overall mean slope angle (α)			Upper rectilinear slope angle (α_u)			Index of concavity (c)		
	UD	GF	Δ	UD	GF	Δ	UD	GF	Δ
Fåbergstølsbreen									
Fa	32·4	31·3	−1·1	33·6	32·3	−1·3	0·17	0·29	0·12
Fb	31·2	31·0	−0·2	32·0	33·0	1·0	0·60	0·32	−0·28
Fc	29·9	27·9	−2·0	33·5	29·7	−3·8	0·26	0·37	0·11
Fd	28·2	25·6	−2·6	34·4	29·9	−4·5	0·15	0·38	0·23
Fe	29·9	28·3	−1·6	34·8	30·2	−4·6	0·12	0·34	0·22
Lodalsbreen									
La	36·7	35·0	−1·7	41·2	38·9	−2·3	0·16	0·15	−0·01
Lb	36·9	34·6	−2·3	38·3	36·9	−1·4	0·52	0·67	0·15
Lc	36·1	32·2	−3·9	41·5	34·3	−7·2	0·07	0·11	0·04
Ld	27·7	27·1	−0·6	32·3	33·0	0·7	0·06	0·13	0·07
Søre Illåbreen									
Sa	35·9	31·4	−4·5	35·9	31·4	−4·5	1·67	1·0	−0·67
Sb	38·5	35·6	−2·9	38·5	35·6	−2·9	0·94	1·0	0·06
Heillstugubreen									
Ha	35·0	34·9	−0·1	36·7	36·3	−0·4	0·41	0·42	0·01
Hb	30·8	30·5	−0·3	30·4	30·6	0·2	0·60	0·47	−0·13
Hc	32·4	31·0	−1·4	33·7	32·1	−1·6	0·55	0·03	−0·52
Hd	30·0	29·9	−0·1	30·0	30·9	0·9	0·23	0·41	0·18
Leirdalen									
LEa	23·2	23·1	−0·1	25·8	25·9	0·1	0·25	0·21	−0·04
LEb	19·9	19·0	−0·9	19·3	24·5	5·2	0·27	0·15	−0·12
LEc	22·3	21·6	−0·7	26·2	26·6	0·4	0·06	0·01	−0·05
LEd	17·7	16·4	−1·3	24·8	24·5	−0·3	0·01	0·05	0·04
LEe	21·9	20·8	−1·1	28·2	28·1	−0·1	0·03	0·12	0·09
Visdalen									
Va	14·4	12·2	−2·2	18·3	21·2	2·9	0·13	0·08	−0·05
Vb	13·3	12·4	−0·9	15·8	16·9	1·1	0·29	0·14	−0·14
Vc	19·9	19·1	−0·8	19·5	21·2	1·7	0·67	0·08	−0·59
Vd	18·3	17·8	−0·5	18·1	20·1	2·0	0·53	0·19	−0·34
Ve	17·7	17·0	−0·7	19·3	21·8	2·5	0·55	0·03	−0·52

SLOPE PROFILE ADJUSTMENT

A total of 25 pairs of ungullied and gullied slope profiles were surveyed to illustrate the modification in profile characteristics due to gullying at each of the field sites. Five examples are shown in Figure 3. With the exception of slopes in Leirdalen and Visdalen, the general form of most of the ungullied drift slopes is that of an approximately straight upper slope resting at gradients between *c*. 30° and *c*. 41° and a basal concavity. Many of these unmodified drift slopes possess an overall form resembling that of rockfall talus slopes (Statham, 1976; Francou and Manté, 1990; Ballantyne and Benn, 1994), though the profiles investigated here result predominantly from the collapse of lateral moraines rather than the accumulation of rockfall debris. Drift slopes in Leirdalen and Visdalen typically have much shallower gradients than those surveyed at other sites. At sites where gully erosion is still active, the effects of paraglacial erosion and redeposition on slope form record only an intermediate stage in paraglacial slope modification; nevertheless, modification of drift slope gradient and geometry is evident to some extent at all sites, and is discussed below.

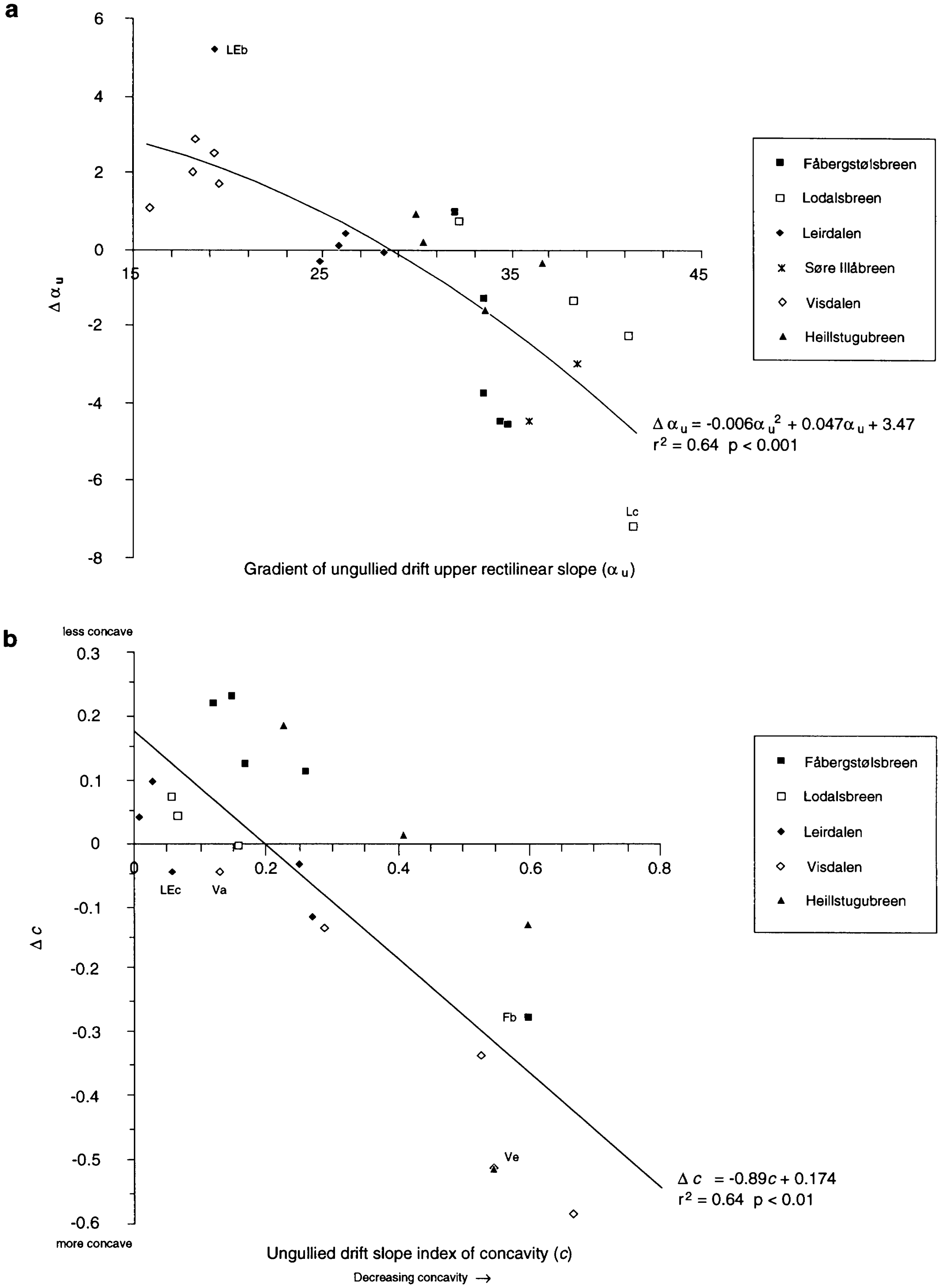


Figure 4. Scatterplots showing (a) change in upper rectilinear slope gradients ($\Delta\alpha_u$) between paired ungullied and gullied profiles against initial upper rectilinear slope gradients (α_u) at all field sites, and (b) change in the index of concavity (Δc) between paired ungullied and gullied profiles against initial index of concavity (c) values at all field sites except Lb, Sa and Sb. This difference represents the degree of change in (a) slope gradient and (b) slope geometry as a result of gullying. In both cases the calculated relationship applies only within the ranges of measured observations (i.e. between 15° and 42° in (a), and a range of c values from 0·01 to 0·67 in (b))

Modification of drift slope gradient

Changes in slope gradient that result from paraglacial gully erosion and redeposition of eroded drift are summarized in Table II. Overall mean slope gradients (α) have been reduced slightly from 13·3–38·5° to 12·2–35·6°, showing a reduction in overall gradient for each set of slope profiles which results from incision of the mid–upper drift slope. The reduction in overall slope gradients observed between ungullied drift profiles and gully floors varies from 0·1° to 4·5°, and the median reduction in overall gradient at all sites is 1·1°. Profiles that exhibit only a slight reduction in overall gradient (e.g. Fb, Figure 3) are generally characterized by a very shallow failure scarp at the gully head, very close to the level of the ungullied drift surface.

Investigation of the upper rectilinear slope angles of drift adjusting to paraglacial conditions is of particular interest, as this is usually the slope unit where incision is initiated and concentrated. As the data in Table II show, 13 of the 25 paired profiles show a decrease in the gradient of the upper straight slope after gullying, whilst 12 paired profiles record an increase in the gradient of the upper rectilinear slope after gullying. Plotting the change in rectilinear slope gradient ($\Delta\alpha_u$) between ungullied drift slopes and corresponding gully floors against initial rectilinear slope gradient reveals a negative non-linear relationship between the two variables significant at $p < 0{\cdot}001$ (Figure 4a). This relationship reveals two trends. First, all sites with initial upper rectilinear slope gradients greater than 33° exhibit a decline in gradient (by as much as 7·2° in profile Lc, Lodalsbreen) due to gully incision. This generally occurs where the upper rectilinear slope rests against a steep rock slope. Conversely, all sites with initial upper rectilinear slope gradients below 25° exhibit steepening as a result of gullying. Many of the Leirdal, Visdal and Heillstugubre profiles record an increase in upper rectilinear slope gradient; indeed, in profile LEb the gully floor rectilinear slope angle is 5·2° steeper than that of the adjacent ungullied drift slope. At sites where upper slope gradient has increased through gullying, gully heads often take the form of shallow translational failures on gently sloping drift. In these cases, where the gully floor meets the ungullied slope at the crest of the drift slope, incision farther downslope inevitably steepens the upper slope gradient. These findings suggest that the nature of paraglacial adjustment of slope profile is to some extent determined by initial slope gradient on steep terrain, and by slope configuration on more gently sloping ground. The data and the summary regression line therefore indicate tendency towards an equilibrium gradient of $29° \pm 4°$, which may be related to the threshold gradient of slope failure and related movement of sediment by hillslope debris flows (*cf*. Innes, 1983; Costa, 1984). Such a scatter is to be expected in view of differing topographic circumstances, localized moisture supply and geotechnical properties of sediments.

Modification of drift slope form

The effects of paraglacial activity on slope geometry are also outlined in Table II for each of the field sites. As these data show, there is considerable spread in the index of concavity values for profiles surveyed up ungullied drift, with c values ranging from 0·01 to 1·67. On 12 sets of profiles there has been a decrease in slope concavity (with the index c increasing by 0·01–0·23), whilst on 13 sets of slope profiles, gully floor profiles are more concave than the corresponding ungullied slope profiles, as identified by decreases in c of 0·01–0·67. A decrease in concavity (i.e. an increase in c) would be expected if incision at the gully head is accompanied with partial infilling of the basal concavity by resedimented drift (*cf*. Ballantyne and Benn, 1994), or if bedrock steps were exposed, increasing the irregularity of the gully floor profile. In contrast, a slope profile would be expected to become more concave if the initial slope form contained marked convexities, or if there was limited incision at the gully head and marked downslope extension of slope foot debris, as is evident when debris slopes are modified by repeated snow avalanche activity (e.g. Luckman, 1977, 1978). Such a pattern emerges in a plot of the difference in the concavity index c between ungullied drift slopes and corresponding gully floors against the ungullied drift c values (Figure 4b). This reveals a negative relationship between the two variables, significant at $p < 0{\cdot}01$. The extreme values for profiles Lb, Sa and Sb distort the shape of the regression relationship, and hence were omitted in the calculation of the regression line. The relationship shows that most of the slopes which were initially relatively concave (ungullied drift $c < 0{\cdot}2$) have become less concave through 'cut' at the top of the slope and 'fill' at the base.

Exceptions to this overall trend include individual slope profiles at Leirdalen (LEc) and Visdalen (Va, Figure 3). Each of these exceptions exhibits shallow failure at the gully head, which accounts for an overall increase in concavity. Conversely, slopes which were initially less concave (with ungullied drift c values $> 0{\cdot}2$) tend to exhibit an increase in overall concavity. In many cases, such profiles also exhibit concave failure scars at gully heads, resulting in an increase in concavity (for example, Fb, Figure 3, and Ve). There are exceptions to this trend, however, notably profile Lb (Figure 3) and profile Sb, which have become less concave despite having relatively high ungullied slope c values. Whilst the ungullied Lb profile has a high c value (0·52), the presence of glacier ice at the slope foot has constrained run-out and cone accumulation, and inhibited any increase in concavity. Similarly, the ungullied part of profile Sb adjacent to the gully contains no basal concavity and has a very high c value of 1·67. Despite these exceptions, the general departure from concavity of the concave slopes and the increasing concavity exhibited by the less concave slopes show an overall tendency towards a range of concavities of approximately 0·0 to 0·4, which relate to the 'concave' and 'concave, minor convexity' descriptive equivalents of Church *et al.* (1979). As with equilibrium gradient values, one would expect slopes to adopt a range of equilibrium concavity values in view of differing topographic, moisture and geotechnical characteristics.

GULLY FORMATION

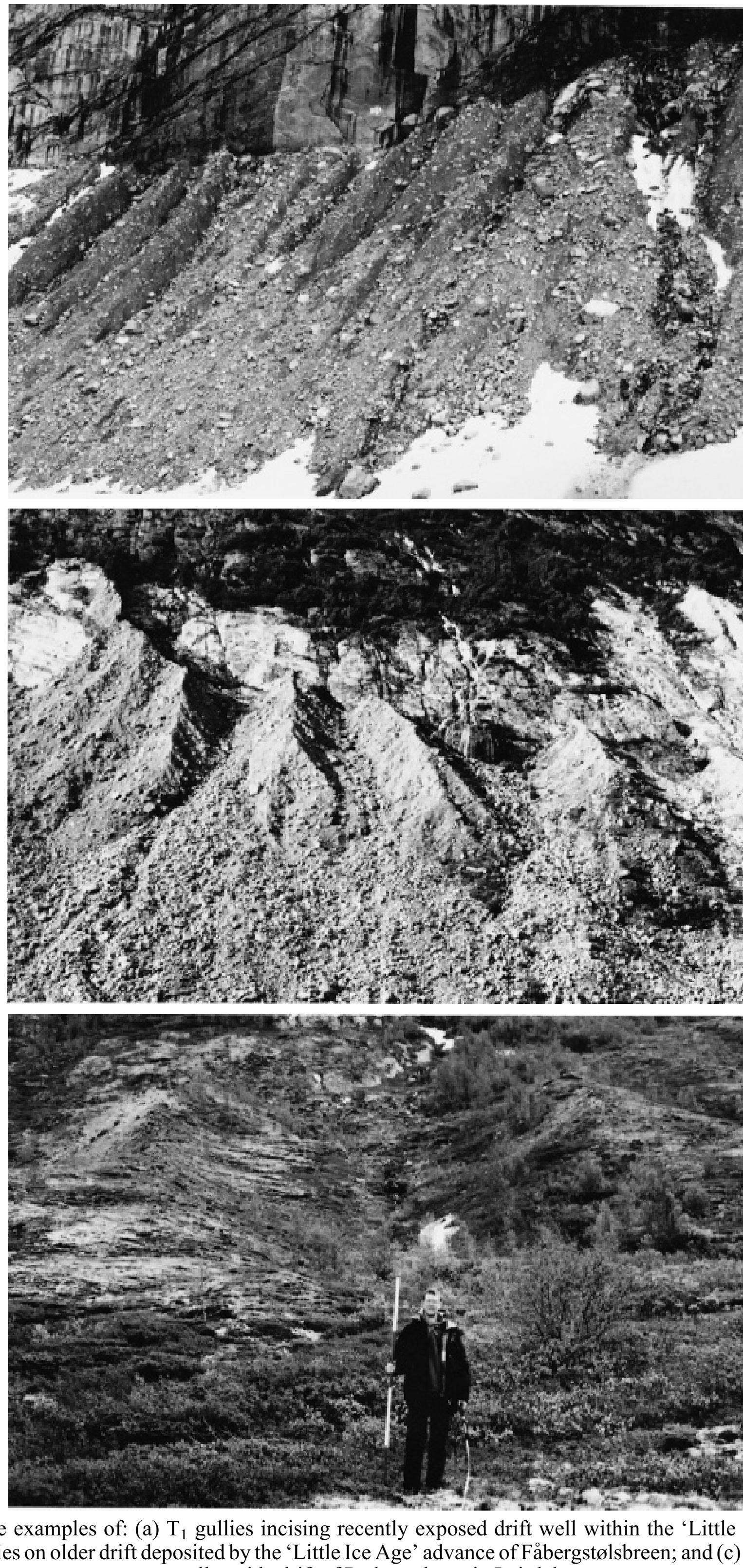
Attention is focused here on the nature of gully development, and concentrates on progressive changes in gully size and shape with age. To permit comparison of the characteristics and dimensions of gullies at different stages of evolution, gully cross-sectional data were placed into three age categories: T_1, T_2 and T_3. Category T_1 includes all the surveyed gullies which lie well within 'Little Ice Age' glacier limits and are close to the present-day ice margins (gullies Fa–Fc, La–Lc, Sa–Sb and Ha–Hd); category T_2 incorporates gullies furthest from the present glacier margin but still within 'Little Ice Age' glacier limits (Fd, Fe and Ld); and category T_3 comprises gullies surveyed outside the maximum limit of 'Little Ice Age' glacier cover (LEa–LEe and Va–Ve). Although there may locally have been some delay in gully initiation following exposure of valley-side drift by glacier retreat, the maximum potential age of the onset of formation of the T_1 gullies is less than that of the T_2 gullies, which is in turn markedly less than that of the T_3 gullies, given the different ages of drift exposure following deglaciation. Comparison of the dimensions and morphological characteristics of the three categories of gullies therefore provides the opportunity to investigate the nature of gully evolution through time. Examples of gullies of these different age categories are shown in Figure 5 and represent different stages in the process of paraglacial slope adjustment.

Modification of gully size with time

Average values of gully depth and width (weighted according to the proportion of slope represented by each cross-section), planimetric area and gully volume are summarized in Figure 6 for each of the three gully age categories. All four parameters tend to increase with increasing gully age. In general, the oldest (T_3) gullies are deeper, wider, cover a greater area and have larger volumes than those in the T_2 category, which are in turn deeper, broader and more extensive than the youngest (T_1) gullies. The differences between the T_1 gullies and T_3 gullies are significant at $p < 0{\cdot}01$ for all four parameters: median depth increases from 1·79 m to 5·61 m; median width from 5·5 m to 44·9 m; median area from 245 m^2 to 11 623 m^2; and median volume from 910 m^3 to 31 330 m^3. Whilst both gully depth and width increase with age, the increase in width is very much greater, and accounts for most of the increase in gully volume. Interestingly, whilst the T_1 and T_2 depth values are statistically indistinguishable, differences in width between the T_1 and T_2 gullies are significant at $p < 0{\cdot}02$. This increase in gully size by widening is well illustrated in Figure 5.

Modification of gully shape with time

Temporal trends in gully shape were assessed in terms of depth/width ratio, maximum sidewall facet angle and the extent of bedrock exposed on gully floors (Figure 7). The first two parameters exhibit rapid changes through time. The median depth/width ratio for T_1 gullies is 0·38, compared to a median value of 0·11 for the



(a)

(b)

(c)

Figure 5. Representative examples of: (a) T_1 gullies incising recently exposed drift well within the 'Little Ice Age' glacier limits at Lodalsbreen; (b) T_2 gullies on older drift deposited by the 'Little Ice Age' advance of Fåbergstølsbreen; and (c) mature T_3 gullies incising valley-side drift of Preboreal-age in Leirdalen

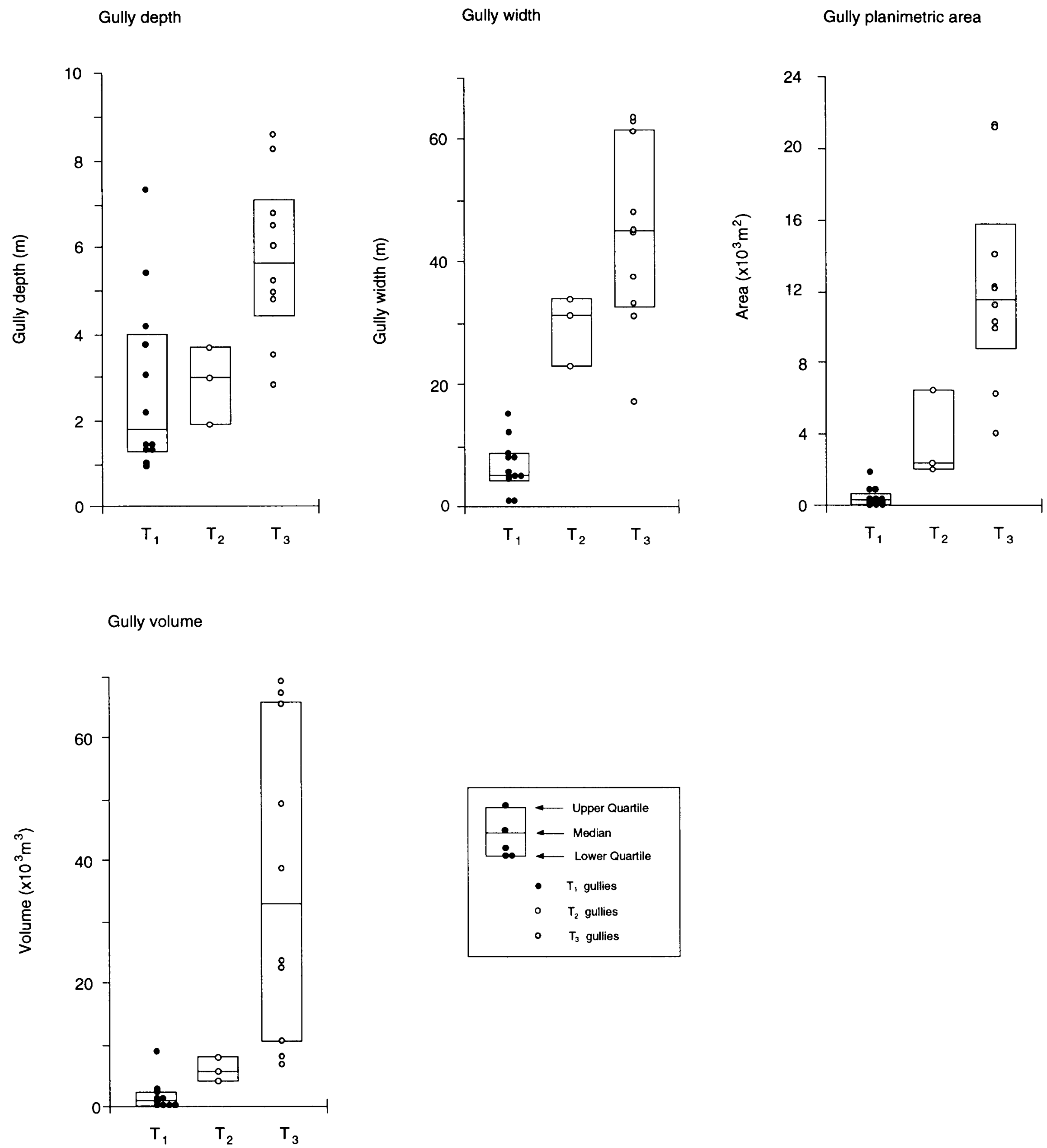


Figure 6. Dispersion diagrams illustrating changes in gully size with gully age. T_1, T_2 and T_3 represent groups of gullies of increasing age at the field sites investigated

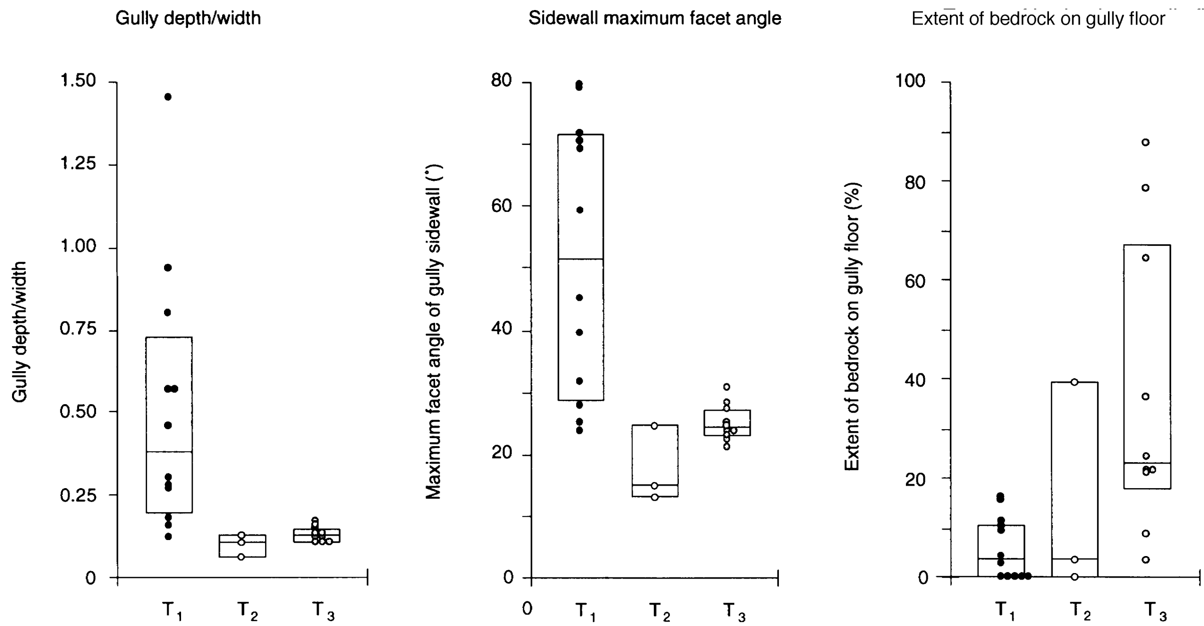


Figure 7. Dispersion diagrams illustrating changes in gully shape and extent of bedrock exposed on the gully floor with gully age. T_1, T_2 and T_3 represent groups of gullies of increasing age at the field sites investigated. Key as in Figure 6

T_2 gullies and 0·13 for the T_3 gullies. Similarly, the median value of maximum sidewall facet angles is 51·9° for the T_1 gullies, 14·7° for the T_2 gullies and 24·2° for the T_3 gullies. For both parameters the T_2 and T_3 values are statistically indistinguishable, but both are significantly lower than the T_1 values at $p < 0{\cdot}05$ (Mann–Whitney two-sample test). Both parameters therefore indicate that the youngest (T_1) gullies tend to be narrow relative to their depth and steep-sided (Figure 5a), but that within a few decades of initial incision both depth/width ratios and maximum sidewall facet angles have declined significantly, and thereafter exhibit limited further change. This pattern implies that following a period of initial rapid incision, gullies undergo progressive widening accompanied by a decline in the gradient of sidewall slopes to < *c*. 25°, after which further widening appears to be accomplished partly by parallel retreat of sidewalls. Given that the T_2 gullies in Jostedalen are as little as 25 years older than the youngest (T_1) gullies in the same area (*cf.* Bickerton and Matthews, 1993; Curry, 1998), the progress of gully development from steep-sided canyons to broad, open gullies at these sites is clearly rapid, consistent with the accumulation and stabilisation of paraglacial debris cones on recently deglaciated terrain within a decadal timescale (Ballantyne, 1995; Harrison and Winchester, 1997).

Gully stabilization

A further point of interest concerning gully development involves slope stabilization. Whilst focusing on much smaller gullies (generally < *c*. 50 m length) than those described above, Harvey (1992) suggested that gully stabilization might be controlled by vegetation encroachment. In the case of the large gully systems surveyed in Norway, vegetation colonization might be expected to be more a response to stabilization of the ground surface than a causal mechanism. A more likely control on gully stabilization is depletion of the upslope supply of sediment. As the data in Figure 7 reveal, the gullies which have been potentially active for the longest time (the T_3 gullies) have a much higher percentage of bedrock exposed on the gully floor (median = 23·2 per cent of total gully length) than the younger (T_1) gully systems (median = 3·7 per cent), particularly in the gully heads. These differences in bedrock exposure are significant at $p < 0{\cdot}005$ (Mann–Whitney two-sample test). Moreover, progressive exposure of bedrock on gully floors explains the reduction

Table III. Amounts and rates of ground surface lowering of steep drift slopes at field sites in Norway

Profile	Average* (m)	Rate† (mm a^{-1})
Fåbergstølsbreen		
Fa	2·4	80
Fb	3·6	119
Fc	5·1	169
Fd	3·5	65
Fe	2·0	38
Mean	*3·3*	*94*
Overall site mean		*42·3*
Lodalsbreen		
La	1·3	67
Lb	3·4	169
Lc	4·8	111
Ld	0·8	19
Mean	*2·6*	*92*
Overall site mean		*73·6*
Søre Illåbreen		
Sa	0·6	2·5
Sb	0·8	3·0
Mean	*0·7*	*2·8*
Overall site mean		*0·02*
Heillstugubreen		
Ha	0·4	5·5
Hb	0·7	8·8
Hc	0·6	8·3
Hd	0·6	8·2
Mean	*0·6*	*7·7*
Overall site mean		*0·41*
Leirdalen		
LEa	1·2	ND
LEb	2·0	ND
LEc	1·1	ND
LEd	4·9	ND
LEe	2·4	ND
Mean	*2·3*	*ND*
Visdalen		
Va	6·1	ND
Vb	3·1	ND
Vc	2·2	ND
Vd	3·2	ND
Ve	2·1	ND
Mean	*3·3*	*ND*

* Average surface lowering since gully initiation.
† Minimum rate of ground surface lowering since gully initiation. Individual figures and mean figures refer to within-gully ground surface lowering. Overall site mean reflects the average rate of ground surface lowering for all (gullied and ungullied) portions of the slope. ND: no data.
Mean values are in italic typeface.

of gully deepening relative to widening illustrated above, in that deepening of individual gullies is rapidly limited by exposure of bedrock on gully floors.

RATES OF SLOPE ADJUSTMENT

A notable feature of previous studies in gully and badland research is that long-term rates of gullying are poorly understood (Bull and Kirkby, 1997). However, the data on gully dimensions (Table I) can be employed to calculate average ground surface lowering since ice retreat at the sites investigated. Moreover, where the timing of paraglacial activity has been established through morphostratigraphic relationships between paraglacial landforms and dated moraine sequences, reliable long-term erosion rates have also been calculated.

Average ground surface lowering within gully systems at the study sites was calculated for individual gullies by dividing total gully volume by gully surface area. Because the timing of deglaciation represents a maximum age for gully initiation, rates of surface lowering implied from these figures are expressed as minima. The results (Table III) show a fairly wide range of individual values, but, with the exception of the Heillstugubre and Søre Illåbre sites where gullies are generally small and immature, the mean site values fall between 2·3 m (Leirdalen) and 3·3 m (Fåbergstølsdalen and Visdalen) of surface lowering (overall median value = 2·4 m), irrespective of age. The gullies on the forelands of Heillstugubreen and (especially) Søre Illåbreen may be regarded as atypical and unrepresentative, having failed to develop to the extent of those elsewhere due to unfavourable constraints. In particular, the drier climate of the Jotunheim forelands appears to inhibit such intense reworking of drift as observed around Jostedalsbreen (Curry, 1998). Indeed, on terrain deglaciated within the last 50 years around Fåbergstølsbreen and Lodalsbreen (*cf.* Bickerton and Matthews, 1993), ground surface lowering has already occurred to depths similar to those of much older gully systems, such as those which were initially incised several millennia ago in Leirdalen. This suggests that, under propitious circumstances, many paraglacial gully systems approach maturity in less than 50 years, implying that, though paraglacial slope modification may continue (intermittently) for millennia, the most active period of paraglacial sediment reworking often occurs within decades of deglaciation. This temporal pattern of drift slope response to deglaciation appears similar to the exponential decline in sediment yield inferred for fluvial environments after ice retreat (Church and Ryder, 1972; Church and Slaymaker, 1989; Harbor and Warburton, 1993).

Table IV. Rates of (a) ground surface lowering and (b) debris accumulation attributable to debris flow activity on steep slopes in various upland environments

Location	Rate (mm a^{-1})	Cover	Source
(a) Surface lowering			
Fåbergstølsdalen, Norway	50–100	Glacigenic	Ballantyne and Benn, 1994
Bergsetdalen, Norway	37–94	Glacigenic	Ballantyne, 1995
Mount Rainier, USA	20–40	Glacigenic	Walder and Driedger, 1994
Howgill Fells, England	55–210	Glacigenic	Harvey, 1987
Tarfala, Lappland	5	Periglacial	Rapp, 1975
Longyear Valley, Spitsbergen	1	Periglacial	Rapp, 1975
Mangawhara, New Zealand	10–80	Volcanic	Selby, 1976
(b) Debris accumulation			
San Rafael Glacier, Patagonia	300–400	Glacigenic	Harrison and Winchester, 1997
Bergsetdalen, Norway	8–44	Glacigenic	Ballantyne, 1995

Data have been adjusted where necessary for convenience of representation.
Rates of ground surface lowering refer to gullied sites and are not averaged over the whole (gullied and ungullied) slope.

For sites where the approximate age of recent deglaciation is known, corresponding minimum rates of ground surface lowering have been calculated by dividing total ground surface lowering at gully sites by maximum time elapsed since deglaciation. As might be expected, the implied surface lowering rates at the two Jostedalsbre sites are significantly higher (median value 80 mm a^{-1}) than those at Heillstugubreen and Søre Illåbreen (median value 6·9 mm a^{-1}), reflecting the limiting constraints on paraglacial activity at the latter. Furthermore, the surface lowering rates associated with the most recent (T_1) gullies at Fåbergstølsbreen and Lodalsbreen are much greater (median = 115 mm a^{-1}) than those for the T_2 gullies at the same sites (median = 38 mm a^{-1}), confirming that the rate of paraglacial erosion of drift is greatest immediately after deglaciation. Possible causes of the declining rate of paraglacial gully erosion through time include progressive stabilization of older gullies as a result of declining sediment supply, lowering of gully floor and/or gully wall gradients, or availability of meltwater (e.g. Ryder, 1971a, b; Fitzsimons, 1996; Curry, 1998).

To give an impression of how these rates compare with rates of surface lowering attributable to debris flow activity in other upland environments, comparative data selected from published sources are presented in Table IV. The range of minimum ground surface lowering values within gullies on the Fåbergstølsbre (38–169 mm a^{-1}; mean 94 mm a^{-1}) and Lodalsbre (19–169 mm a^{-1}; mean 92 mm a^{-1}) forelands are both mutually consistent and overlap previous estimates of erosion rates in gullies at sites around Jostedalsbre based on more limited surveys of gully dimensions and volumes of debris cones. Ballantyne and Benn (1994) found that ground surface lowering by paraglacial debris flows since AD 1943 in Fåbergstølsdalen was equivalent to a minimum erosion rate of 50–100 mm a^{-1}, well within the above ranges, though they also estimated that the size of the largest gully represented an erosion rate of $\geq$ 200 mm a^{-1}. (However, this gully was unusual as it contained a perennial stream which clearly plays a major role in the rapid evacuation of sediment in this gully.) Similarly, surveys of the dimension of debris cones in neighbouring Bergsetdalen by Ballantyne (1995) imply average rates of sediment accumulation of 8–44 mm a^{-1}, with an inferred average rate of drift removal of 37–94 mm a^{-1} at one site. These overlapping ranges of rates of paraglacial gully erosion at the three locations suggest that they may be regarded as being reasonably representative for recently deglaciated steep drift-covered slopes in western Norway. These rates are also broadly similar to those calculated by Harvey (1987) for ground surface lowering associated with recent gully erosion in glacial deposits in northern England, but are markedly lower than Harrison and Winchester's (1997) surprisingly high estimates for paraglacial sediment accumulation on debris cones in extremely wet, recently deglaciated environments in Patagonia. Although similar to Selby's (1976) estimated rate of gully erosion in unconsolidated volcanic deposits in New Zealand, the rates of paraglacial debris flow erosion and resedimentation generally exceed those attributable to debris flow activity outside a paraglacial setting.

By collating over 400 published rates of slope processes worldwide, Young and Saunders (1986) presented typical rates of ground loss attributable to surface wash (0·002–0·2 mm a^{-1}), solution (0·002–0·1 mm a^{-1}) and landsliding (0·1–10 mm a^{-1}), and cited 1–5 mm a^{-1} as representative of rates of overall surface lowering in steep, glacial environments. Comparison of these erosion rates with those calculated for paraglacial gully development at Fåbergstølsbreen and Lodalsbreen highlights the extreme rapidity with which paraglacial erosion of recently deglaciated terrain occurs, even though this is focused in gully systems and thus not necessarily representative of general rates of ground surface lowering, except on terrain where gully systems coalesce with no intervening ungullied ground. Overall rates of ground surface lowering for both gullied and ungullied slopes at Fåbergstølsbreen and Lodalsbreen were estimated by multiplying the mean ground surface lowering rates within gullies by the proportion of the overall slope occupied by gullies within the uppermost kilometre of each foreland (Table III). This calculation yielded overall values of *c*. 42 mm a^{-1} at Fåbergstølsbreen and *c*. 74 mm a^{-1} at Lodalsbreen, roughly an order of magnitude higher than the general rate for steep glaciated environments estimated by Young and Saunders (1986), and again emphasizing the extreme rapidity of drift slope erosion and sediment transfer associated with paraglacial activity shortly after exposure of steep drift slopes from under a cover of glacier ice.

In summary, the new and published data collectively indicate that a very wide range of rates may be associated with paraglacial gully development in recently deglaciated terrain, ranging from the relatively low minimum erosion rates (2·5–8·8 mm a^{-1}) calculated for sites in Jotunheimen (Heillstugubreen and Søre Illåbreen; Table IV) to the extremely rapid rates (300–400 mm a^{-1}) of resedimentation suggested by Harrison

and Winchester (1997) for debris cones on the San Rafael Glacier foreland in Patagonia. However, even the relatively low erosion rates calculated for the Jotunheim sites greatly exceed 'normal' erosion rates in many other environments (Saunders and Young, 1983; Young and Saunders, 1986), often by several orders of magnitude.

CONCLUSIONS

Firstly, paraglacial slope adjustment at the sites investigated operates primarily through the development of gully systems cut into steep valley-side drift deposits. The overall pattern is one of stripping of glacigenic sediment from the upper parts of the drift slope and redeposition of this sediment in debris cones downslope. The net result is an overall lowering of average gradient (by up to 4·5°) along gully axes, evident at all the sites investigated. Further paraglacial activity may lower the overall gully-floor gradient below the threshold gradient of debris flow initiation, thereby leading to progressive atrophy and ultimate stabilization. However, the detailed form of slope adjustment varies considerably. In all cases where ungullied drift slopes possess an initial upper rectilinear slope unit steeper than 33° and exhibit pronounced concavity, gully incision has lowered the upper slope gradient and resulted in partial infill of the basal concavity. Conversely, on less concave drift slopes where the initial upper slope unit gradient is below 25° and initial failure is shallow, slight steepening of the upper slope and an increase in overall concavity have often occurred. Though there are exceptions to this pattern, in general paraglacial slope profile adjustment appears to be characterized by a convergence of slope profiles towards an 'equilibrium form' with an upper rectilinear slope gradient at $29° \pm 4°$ and a range of concavities of approximately 0·0 to 0·4. It is notable that several authors have observed that the minimum threshold for the initiation of hillslope debris flows on a range of materials is often around 27–30° (e.g. Takahashi, 1981; Innes, 1983; Costa, 1984).

Secondly, the three categories of gully age investigated in Norway may be seen as representing different stages in gully development. The youngest gullies form deep, steep-sided canyons, but very rapidly broaden out and become much larger conduits of sediment transfer. After initial incision, further gully deepening is limited, but gullies become progressively wider as sidewall collapse and other processes move sediment towards the gully floor, where it is evacuated by frequent debris flows. Initial gully widening takes the form of sidewall decline, but after sidewalls have relaxed to a gradient of *c*. 25°, parallel retreat appears to predominate. Gully widening progressively reduces the width of intervening ridges of ungullied drift. The final form of mature paraglacial gully systems consists of an upper bedrock-floored source area, a mid-slope area of broad gullies whose sidewalls rest at stable, moderate ($<$ *c*. 25°) gradients, and a lower slope zone where gullies discharge onto the surfaces of coalescing debris cones and fans. Some gullies appear to have attained this final form and stabilized within decades of initiation, following exhaustion of readily entrainable sediment on the upper part of the slope.

Finally, at all but the least active field sites, paraglacial activity has transformed steep drift-mantled valley sides into gullied slopes where an average of *c*. 2–3 m of surface lowering has taken place within the gullied area. Under favourable conditions, gullies cut into recently deglaciated drift slopes have reached these levels of surface lowering in less than 50 years. At the most active sites in the Jostedalsbre area, these average amounts imply minimum erosion rates averaging *c*. 90 mm a^{-1} since gully initiation, though in the Jotunheim foreland sites average erosion rates have been much lower, possibly as low as *c*. 2·5 mm a^{-1}. However, even these relatively low rates greatly exceed 'normal' erosion rates in other environments, often by several orders of magnitude, thus highlighting the extreme rapidity of paraglacial erosion of recently deglaciated drift-mantled slopes.

ACKNOWLEDGEMENTS

This research was supported by a University of St Andrews Postgraduate Studentship, a Russell Trust Award and a Quaternary Research Association Young Persons Research Award. The research was undertaken whilst at the University of St Andrews, under the supervision of Professor Colin Ballantyne, Dr John Walden and Dr Charles Warren. The author thanks M. Burn, A. Clarke, T. Oldershaw and B. Schaafsma for field assistance,

Mr C. Cameron for technical assistance, and Professor Colin Ballantyne for his helpful comments on the original draft of this paper.

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